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(Dated: November 27, 2006)

Submitted to Physical Review Letters

GANIL P 06 10

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Measurements of de–excitation gamma–rays in coincidence with target-like residues produced in deep inelastic transfer reactions of ^{238}U on a ^{48}Ca target at an energy near the Coulomb barrier are presented. A systematic analysis of the measured low lying states in the odd and even neutron-rich Ca isotopes shows the absence of a predicted shell closure at $N = 34$ in neutron-rich calcium isotopes.

PACS numbers: 21.60.Cs, 25.70.Lm, 23.20.Lv, 27.40.+z

Energy shells or periodic enhancements of level densities from its mean value, as a function of energy, is a general feature arising from quantum effects in finite size systems ranging from atoms, nuclei to metallic clusters. Advances in the measurements of the size of large metallic clusters provided opportunities for the search of the existence of "super shells" and for "magic" numbers different from those in atomic and nuclear physics [1]. The improved sensitivity of experimental techniques, both with low-intensity radioactive ion beams and high-intensity stable beams, played an analogous role in the quest for understanding the evolution of the ordering of single-particle (shell model) states or new "magic numbers", as a function of isospin in nuclei far from stability [2]. Intense theoretical efforts are underway to obtain new effective shell model interactions which can explain and predict features of nuclei far from stability [3–6].

With the addition of protons in the $\pi 1f_{7/2}$ orbital, moving from Ca to Ni, the strongly attractive proton–neutron spin–flip interaction [6] is known to modify the ordering of the levels in the fp–shell from $2p_{3/2}$, $2p_{1/2}$ and $1f_{5/2}$ in ^{49}Ca to $2p_{3/2}$, $1f_{5/2}$ and $2p_{1/2}$ in ^{57}Ni [7]. Similar migration of single particle levels for changing N/Z asymmetry gives rise to weakening of known shell closures at $N = 8,\ 20,\ 28$ and the appearance of new ones, such as, $N = 14,\ 16,\ 32$. The recent prediction [5] of the existence of a "magic number" at $N = 34$ (first predicted more than thirty years back [8]) initiated a large experimental effort [9–12] (and references therein), in neutron-rich nuclei around Ca. These measurements confirmed the existence of a sub shell closure at $N = 32$ (between the $p_{3/2}$ and $p_{1/2}$ orbitals) but no evidence for the appearance of a new gap at $N = 34$ was reported in Ti and Cr isotopes [9–11]. These nuclei are easier to study due to their lower N/Z values, but the presence of valence protons outside the $Z = 20$ shell reduces their sensitivity to the neutron configuration (hence the $N = 34$ closure) as compared to the more exotic neutron-rich isotopes of Ca. The study of these neutron-rich Ca isotopes also provides a good handle to explore the role of the $T = 1$ term of nucleon-nucleon interaction in the evolution of shell structure far from stability.

Calculations using the two most recent shell model interactions, GXPF1A [5] and KB3G [3] and its modification KB3GM [13], derived for nuclei having their valence nucleons in the pf–shell are in good overall agreement with the measured level schemes [9, 10]. The GXPF1A interaction is obtained from a systematic fit to experimental data starting from a realistic interaction, while the KB3GM is obtained from empirical modifications of the monopole part of the realistic nucleon–nucleon interaction. Shell model calculations using the GXPF1A interaction predicted a new shell closure at $N = 34$ (between the $p_{1/2}$ and $f_{5/2}$ orbitals), making $^{54}_{20}Ca_{34}$ a new doubly magic nucleus. Contrary to the above, the use of KB3G/KB3GM interaction do not predict the appearance of this shell closure [13]. It should be noted that both interactions predict the low lying states in the Ca isotopes to be dominated by valence single neutron excitations.

The rapidly decreasing cross section associated with the increasing N/Z values for ^{53,54}Ca makes them difficult to characterize. Both the lack of experimental observation of ^{54}Ca and the small probability to populate the $f_{5/2}$ state in ^{53}Ca through β–decay make it difficult to directly verify this prediction. Therefore, in the present work excited states corresponding to dominant neutron single-particle configurations in neutron-rich isotopes of Ca ($^{50-52}$Ca) have been populated and identified to obtain directly the difference in energy between the $p_{1/2}$ and $f_{5/2}$ orbitals and thus the shell gap at $N = 34$.

The measurements were made at GANIL using typical beam currents of $\simeq 2$ pnA of ^{238}U from the CSSI cyclotron at an energy of 1.310 GeV incident on an isotopically enriched (96%), 1 mg/cm^2 thick, ^{48}Ca target. The resulting target-like residues produced in deep inelastic transfer reactions [2] were detected and identified using the large acceptance spectrometer VAMOS [14]. The coincident prompt γ–rays from the target-like residues were detected using 11 segmented clover detectors of the EXOGAM [15] array (photopeak efficiency $\sim 9\%$ at 1 MeV)

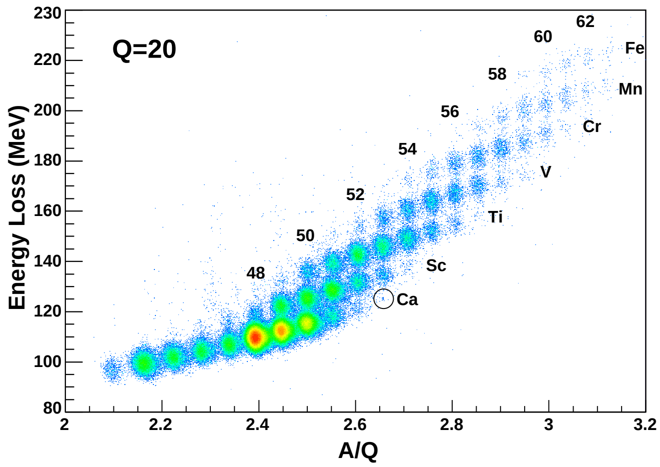

FIG. 1: (color online) A typical spectra for a single Si detector in the focal plane of the spectrometer. Energy loss detected in an ion chamber versus the derived mass over charge for a selected charge state, $Q = 20$. The position of ^{53}Ca is indicated by the circle and the various nuclei are indicated.

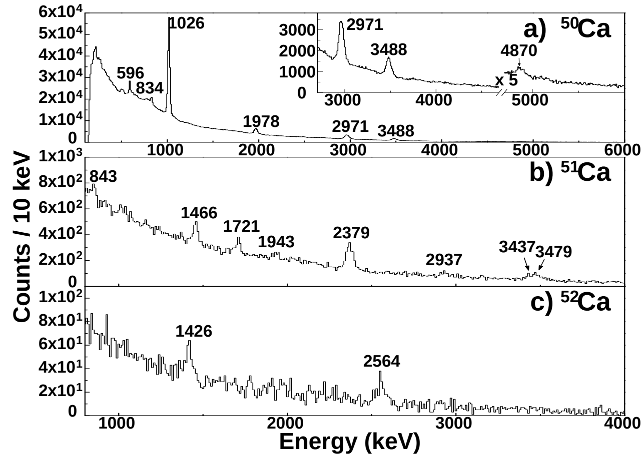

FIG. 2: Doppler corrected γ–ray spectra obtained in EXOGAM in coincidence with VAMOS for different isotopes of Calcium a) ^{50}Ca, the inset shows the high energy part of the spectra b) ^{51}Ca and c) ^{52}Ca.

surrounding the target. The optical axis of the VAMOS spectrometer was placed at 35 degrees (near a calculated grazing angle) with respect to the beam axis. The reaction products were identified from two-dimensional matrices of energy loss (ΔE) and mass-over-charge (A/Q) for each charge state. Figure 1 shows a typical identification matrix for one section of the focal plane clearly demonstrating the unambiguous identification (Z, A) of the various target-like residues. Further experimental details and results are given in Ref. [16]. As can be seen from Fig. 1, ^{53}Ca is the most neutron-rich isotopes of Ca produced in the present work ($N/Z \sim 1.65$). The angle between the segment of the clover detector and the reconstructed velocity from the VAMOS spectrometer was used to correct for the Doppler effect on an event by event basis. The resulting γ–ray spectra in coincidence with the neutron-rich Ca isotopes identified in VAMOS, are shown in Fig. 2. Low statistics in the gamma spectrum of ^{53}Ca prevented a clear identification of the position of its excited states.

In the present work γ–γ coincidences and relative intensities were used to obtain the level schemes. Due to the fast falling and low production cross sections, a limited use of γ–γ coincidences could be made in ^{51}Ca. The relative intensities of various transitions as a function of the excitation energy in the fragment were used as an additional aid for the placement of the γ–rays. The excitation energy of the detected fragment was constrained from the measured kinetic energy of the target-like residue in the focal plane. Such a method, to the best of our knowledge, has been employed for the first time. In ^{50}Ca the 1978.2(0.6) keV γ–ray was observed in coincidence with the 1026.2(0.3) keV transition and has been assigned to arise from the decay of a 2^+_2 and not from a 0^+ state [17], based on the higher expected energy of the 0^+ in ^{48}Ca. Other transitions seen in Ref. [2] and also in the present work are not shown in Fig. 3. In ^{51}Ca the 1943.4(5.7), 1466.3(1.6) and 843(27) keV transitions were not observed earlier. A direct feeding of the 2^+ state in ^{52}Ca found in the present work, was not observed in Ref. [18]. As seen from Fig. 2, a striking feature of the present work is the relatively large intensities of the 2971.4(0.6) keV, 1426.1(3.2) keV γ–rays in ^{50}Ca and ^{52}Ca respectively. The γ–rays have been assigned to the de–excitation of the octupole core excited state at around 3.9 MeV (3^-) [2, 18]. The equally strong feeding of the state at a similar energy in ^{51}Ca decaying by the 1466.3 keV transition suggests it to be an equivalent state.

A restrictive level scheme obtained from the present work for the neutron-rich isotopes of $^{50-52}$Ca along with shell model calculations using the GXPF1A interaction is shown in Fig. 3. High lying states identified with the $3^-(2^+, 4^+)$ states in ^{48}Ca involving proton (neutron) core excitations across the $Z = 20$ ($N = 28$) gap are also shown. In the following qualitative discussion, simple shell model analysis in terms of a sequential occupancy of the shell model states, the doubly closed shell nature of $^{48}_{20}$Ca$_{28}$ and the neutron single particle energies in $^{49}_{20}$Ca are used to identify and interpret the expected dominant neutron configurations of the observed low lying states in $^{50-52}$Ca. These are then used to obtain an estimate of the shell gap at $N = 34$. The validity of the above approach was confirmed by performing large scale shell model calculations using the GXPF1A, KB3G and KB3GM interactions.

The ground state of ^{50}Ca corresponds to a pair of valence neutrons in the $p_{3/2}$ orbit coupled to $J^\pi = 0^+$ and a closed ^{48}Ca core. The breaking of this pair will give

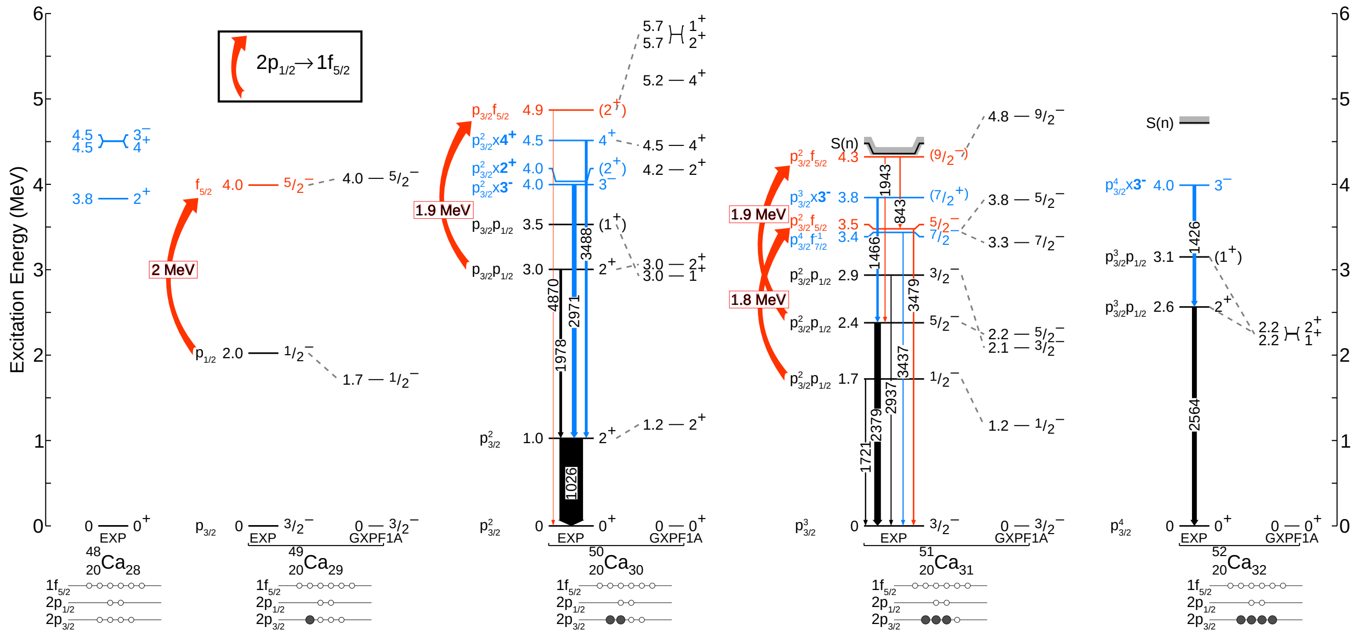

FIG. 3: (color online) A restrictive level scheme of the Ca isotopes obtained from the present measurement. The data for 1^+ in ^{50,52}Ca and 2^+_3 in ^{50}Ca are from Ref. [12, 17]. The neutron separation energy S_n and the natural occupancy of the neutrons in the ground state is also shown. The open circles represent the unfilled states. The curved arrows connect states differing only with the promotion of a single neutron from $p_{1/2}$ to $f_{5/2}$ orbit with no change in the ($p^n_{3/2}$, n = 0, 2) neutrons. The corresponding difference in energies are labeled (see text).

rise to a 2^+ state at $\sim$ 1 MeV consistent with the known pairing energy. No other states with only two neutrons in the $p_{3/2}$ orbital are possible. The next natural excitation arises from the promotion of a neutron to the $p_{1/2}$ orbital. This state is expected to be at 2 MeV above the 2^+_1 state in analogy with the the first excited state in ^{49}Ca. Only two states, namely the 1^+ and 2^+, can be obtained from this $p_{3/2}p_{1/2}$ configuration. The requirement of anti-symmetrization causes the spatial overlap of the wave function of two particles in the $p_{3/2}$ and $p_{1/2}$ orbits in the 1^+ state to be inhibited relative to that in the 2^+ state [19]. This leads to the 2^+ being more bound relative to the 1^+ state. Based on the energy of the lowest excited states in ^{48}Ca, the core-excited states are expected to contribute around 4 MeV. The assignment of a 3^-, 2^+_3 and 4^+ states [2, 17] is consistent with this expectation. The state at 4.9 MeV is identified with the $p_{3/2}f_{5/2}$ excitation. This is based on its position being $\sim$ 4 MeV above the 2^+_1 ($p^2_{3/2}$) state and $\sim$ 2 MeV above the 2^+_2 ($p_{3/2}p_{1/2}$) consistent with that in ^{49}Ca. The observed direct transition to the ground state precludes a 0^+ or 4^+ assignment to this state.

In ^{52}Ca the $p_{3/2}$ orbit is fully occupied in the ground state, preventing further re–coupling of these nucleons, thus accounting for the absence of state analogous to the 2^+_1 in ^{50}Ca. Hence the energy of the first 2^+ in ^{52}Ca is determined by the excitation of a neutron from the $p_{3/2}$ to $p_{1/2}$ orbital and consistent with those in ^{49,50}Ca.

The second excited state is analogous to the 1^+ in ^{50}Ca. The tentative assignment of the level at 4.0 MeV to be a 3^- [12, 18] can be made firm, based on a uniformly strong feeding of these states in all the neutron-rich isotopes of Ca as discussed earlier. The knowledge of the above states is now used to describe the structure of ^{51}Ca.

The ground state of ^{51}Ca can be described as three neutrons occupying the $p_{3/2}$ orbit leading to the only possibility of a $3/2^-$ state. The excitation of a single neutron from the $p_{3/2}$ to $p_{1/2}$ orbital with the remaining two neutrons coupled to $J^\pi = 0^+$ leads to the first excited $1/2^-$ state. The observed excitation energy for this state (1.7 MeV) is $\sim$ 300 keV smaller than the value expected from the energy difference between the two lowest 2^+ states in ^{50}Ca or that of the corresponding single-particle states in ^{49}Ca. This arises from the decreased pairing of the $p^2_{3/2}$ configuration in the ground state as compared to that in the first excited state. Only two additional states namely the $3/2^-$ and $5/2^-$ can be formed from the $p^2_{3/2}p_{1/2}$ configuration as in ^{50}Ca, where the two neutrons in the $p_{3/2}$ orbital recouple to $J^\pi = 2^+$. The $5/2^-$ state is lower in energy relative to $3/2^-$ in analogy with the corresponding 1^+ and 2^+ states in ^{50}Ca. Higher lying states are expected to be formed either by excitation of one neutron to the $f_{5/2}$ state or by core excitations. The $5/2^-_2$ state arises from excitation of one neutron to the $f_{5/2}$ orbit with the remaining $p_{3/2}$ neutrons coupled to $J^\pi = 0^+$. This state is expected to be $\sim$ 2 MeV above the $1/2^-$ state (from ^{49}Ca and ^{50}Ca); the observed energy difference is ~ 1.8 MeV (as indicated in Fig. 3). The breaking of the $p_{3/2}$ pair in the $p^2_{3/2}f_{5/2}$ configuration will result in a multiplet of states ($1/2^- \leq J^\pi \leq 9/2^-$), due to the coupling of the $f_{5/2}$ and the 2^+ ($9/2^-$ is expected to be the lowest of the multiplet). This $9/2^-$ state is expected to lie ~ 0.7 MeV above the $5/2^-_2$ state arising from the difference in corresponding $p^2_{3/2}p_{1/2}$ states; $1/2^-_1$ and $5/2^-_1$ in agreement with the observed difference of ~ 0.8 MeV. The observation of the γ–transitions (1943 keV, 843 keV) corroborates the above assignment thus excluding the states at 3.5 MeV and 4.3 MeV to be associated with excitation of the core. In analogy with ^{50}Ca, the remaining states at 3.4 MeV and 3.8 MeV can be identified with excitations of the ^{48}Ca core, i.e. the $(p^4_{3/2}f^{-1}_{7/2},\ 7/2^-)$ and $(p^3_{3/2} \times 3^-,\ 7/2^+)$ respectively.

The configurations of levels in terms of the valence neutrons and ^{48}Ca core-excitations have been discussed above and states having $p_{1/2}(p^n_{3/2},\ J^\pi)$ and $f_{5/2}(p^n_{3/2},\ J^\pi)$ configuration have been identified. The energy difference between these states is shown to have an almost constant value of ~ 1.9 MeV (indicated in Fig. 3). This can be taken to represent the gap between the $p_{1/2}$ and $f_{5/2}$ neutron orbitals. Small corrections to the derived gap can arise from the differences in the residual interaction of the $p_{1/2}$ or $f_{5/2}$ neutron with the $(p^n_{3/2},\ J^\pi)$ spectator configuration. A simple extrapolation to ^{53}Ca will imply that the corresponding $5/2^-$ state $(f_{5/2}(p^4_{3/2},\ 0^+))$ to be $\sim$ 1.9 MeV above the $1/2^-$ ground state $(p_{1/2}(p^4_{3/2},\ 0^+))$. Similarly, the first excited state in ^{54}Ca is expected to be slightly higher than this value due to the additional stability of the ground state $(p^2_{1/2}, 0^+)(p^4_{3/2},\ 0^+)$, similarly to ^{52}Ca. A similar analysis can also be applied to the model predictions [5] for the various levels shown in Fig. 3. The corresponding energy differences between the $p_{1/2}$ and $f_{5/2}$ orbitals are ~ 2.3, 2.7 and 2.6 MeV in ^{49}Ca,^{50}Ca and ^{51}Ca respectively. These are consistent with the calculated energies of the $5/2^-$ state in ^{53}Ca and that reported in Ref. [5] for the first 2^+ at 2.9 MeV in ^{54}Ca. The equality of the predicted energies of these states in ^{53,54}Ca suggest the cancellation or/and the absence of neutron–neutron correlations in ^{54}Ca.

Further, as can be seen from Fig. 3, a comparison of the experimental results with the predictions of the GXPF1A interaction shows a systematic lowering (by $\sim$ 0.6 MeV) of states with a $\left|p_{3/2}p_{1/2},\ 1^+\right\rangle$ parentage of the wave function (the 1^+ states in ^{50,52}Ca and $1/2^-$, $3/2^-$ in the ^{51}Ca). Such a behavior is expected to arise from an increased binding due to an incorrect $\left\langle p_{3/2}p_{1/2},\ 1^+ \left|V\right| p_{3/2}p_{1/2},\ 1^+\right\rangle$ two body matrix element. This was verified both by a comparison of the relevant matrix elements in both the interactions and their effect on the relevant levels in ^{53,54}Ca. Additionally the states involving a $\left|p_{3/2}f_{5/2},\ J^\pi\right\rangle$ parentage can be seen to be calculated systematically to have a smaller binding energy compared to the experimental levels by a few hundred keV. It can be seen that due to these reasons, the predicted energy spacing between the $p_{1/2}$ and $f_{5/2}$ orbitals [5] is too large compared to that experimentally obtained, thus giving no real strong hint for the appearance of a N=34 "magic" gap. The present work also shows that the importance of the study of odd nuclei (such as ^{51}Ca in the present case) to constraint extrapolations of shell model interactions.

In summary, a shell model interpretation of the measured levels of the neutron-rich isotopes of Ca shows that energy spacing between the $2p_{1/2}$ and $1f_{5/2}$ neutron orbitals is almost constant going from $^{49-52}$Ca and when extrapolated to ^{53,54}Ca, shows that $N = 34$ cannot be considered as a new magic number as predicted earlier. The present work also presents new limits of experimental sensitivity, reached using deep inelastic transfer reactions, to access to a wide variety of states with different configurations including odd nuclei, necessary to study structural changes far from stability.

The authors are thankful to the GANIL team for their flawless operation of the facility. They would like to thank B. Lecornu, C. Marie, J. Ropert, G. Voltolini Ch. Spitaels and G. Fremont for their dedicated and untiring efforts in the operation of the detections systems and M. Rousseau and R. Chapman for their asssitance in taking the data. They also thank the Strasbourg-Madrid shell model collaboration for providing the shell model interactions and many stimulating discussions and K. Hyde for critical reading of the manuscript. The INTAG under EURONS is thanked for support.

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[1] H. Nishioka, Z. Phys. D **19**, 19 (1991).
[2] R. Broda, J. Phys. G **32**, R151 (2006).
[3] E. Caurier *et al.*, Rev. Mod. Phys. **77**, 427 (2005).
[4] B. A. Brown *et al.*, Phys. Rev. C **74**, 034315 (2006).
[5] M. Honma *et al.*, Phys. Rev. C **69**, 034335 (2004); M. Honma *et al.*, Eur. Phys. J. A **25** Suppl. 1, 499 (2005).
[6] T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005).
[7] A. Bohr and B. R. Mottelson, Nuclear Structure (Benjamin, Reading, MA, 1975), Vol. I.
[8] M. Beiner *et al.*, Nucl. Phys. A **249**, 1 (1975).
[9] D. C. Dinca *et al.*, Phys. Rev. C **71**, 041302(R) (2005).
[10] B. Fornal *et al.*, Phys. Rev. C **72**, 044315 (2005).
[11] N. Marginean *et al.*, Phys. Lett. B **633**, 696 (2006).
[12] F. Perrot *et al.*, Phys. Rev. C **74**, 014313 (2006).
[13] E. Caurier *et al.*, (to be published.)
[14] H. Savajols *et al.*, Nucl. Phys. A **654**, 1027c (1999).
[15] J. Simpson *et al.*, Acta Phys. Hung. New Ser.: Heavy Ion Phys. **11**, 159 (2000).
[16] S. Bhattacharyya *et al.*, (to be published).
[17] P. Baumann *et al.*, Phys. Rev. C **58**, 1970 (1998).
[18] A. Gade *et al.*, Phys. Rev. C **74**, 021302(R) (2006).
[19] R.F. Casten, p 103, Oxford Univ. Press (2001).